研究会：「中間エネルギーイオンビームによる物理」 at RCNP (April 3, 2002)

結晶場による相対論的重イオンのコヒーレント共鳴励起の観測

T. Azuma
Department of Physics, Tokyo Metropolitan University, Japan

Y. Takabayashi, T. Ito, Y. Yamazaki, K. Komaki
Institute of Physics, University of Tokyo, Japan

E. Takada, T. Murakami
National Institute of Radiological Sciences, Japan

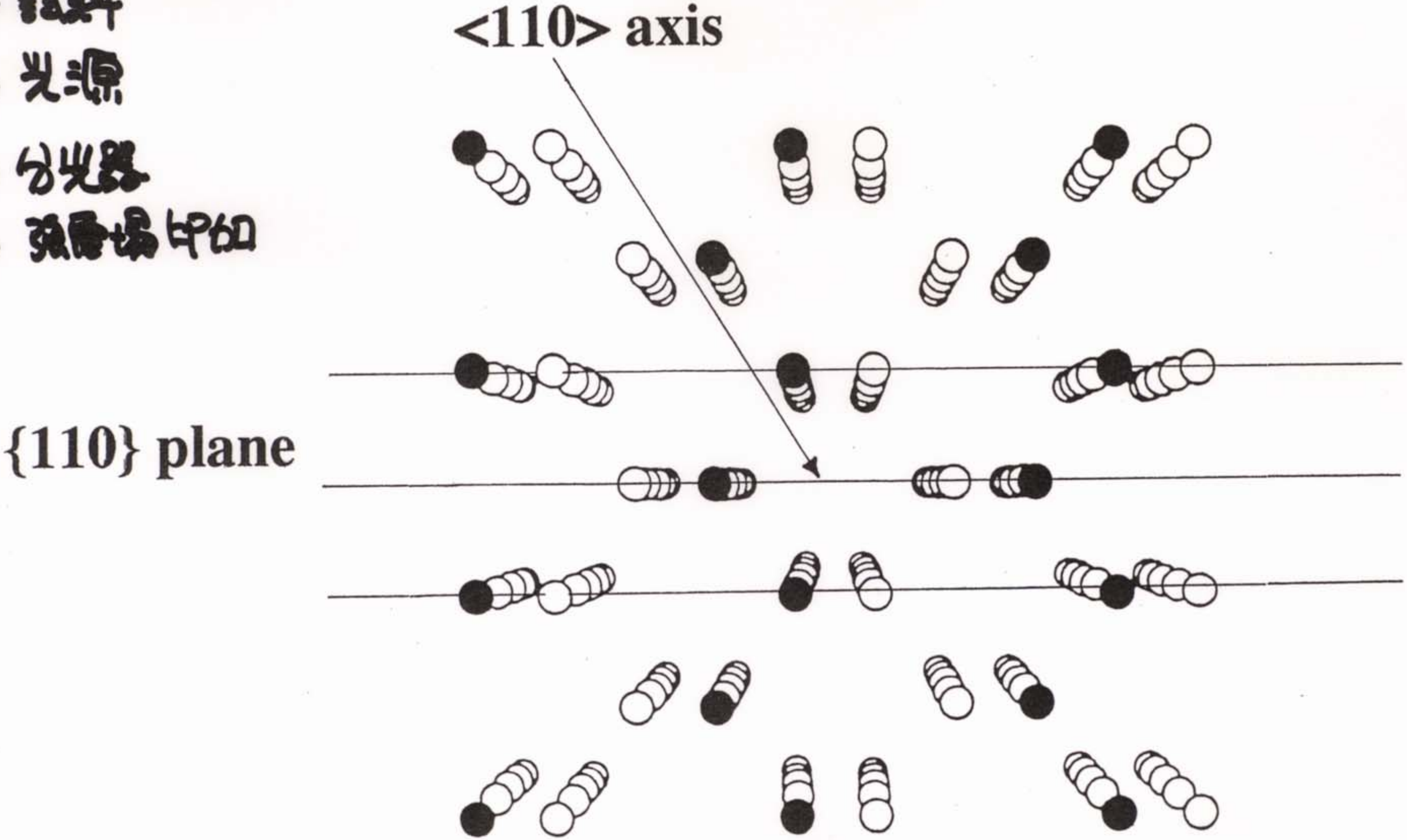
Si crystal

→ 試料

→ 光源

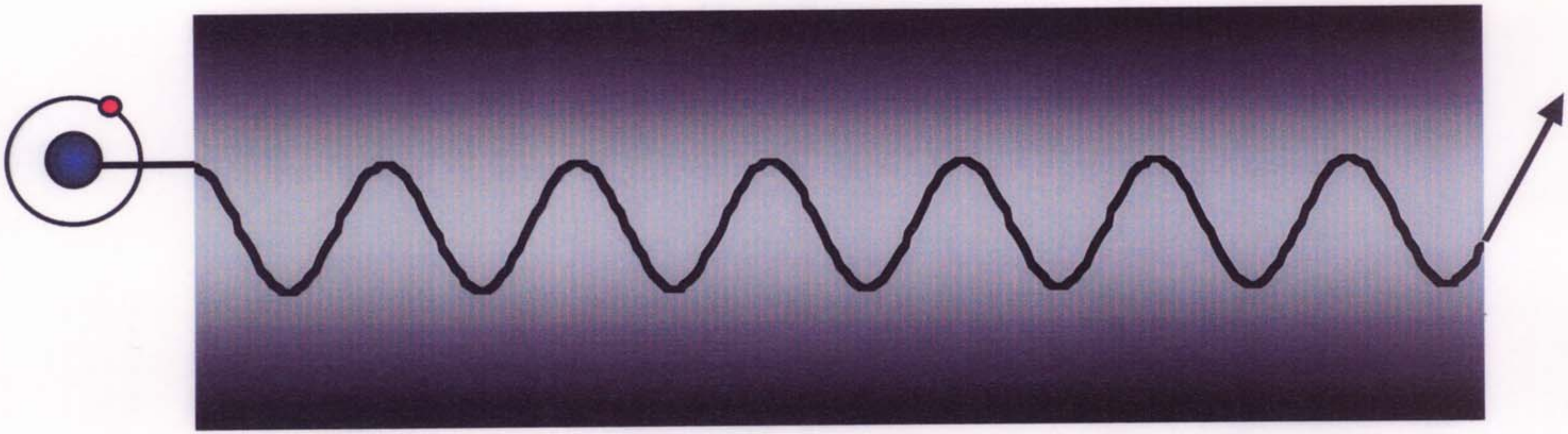
→ 分光器

→ 強電場印加

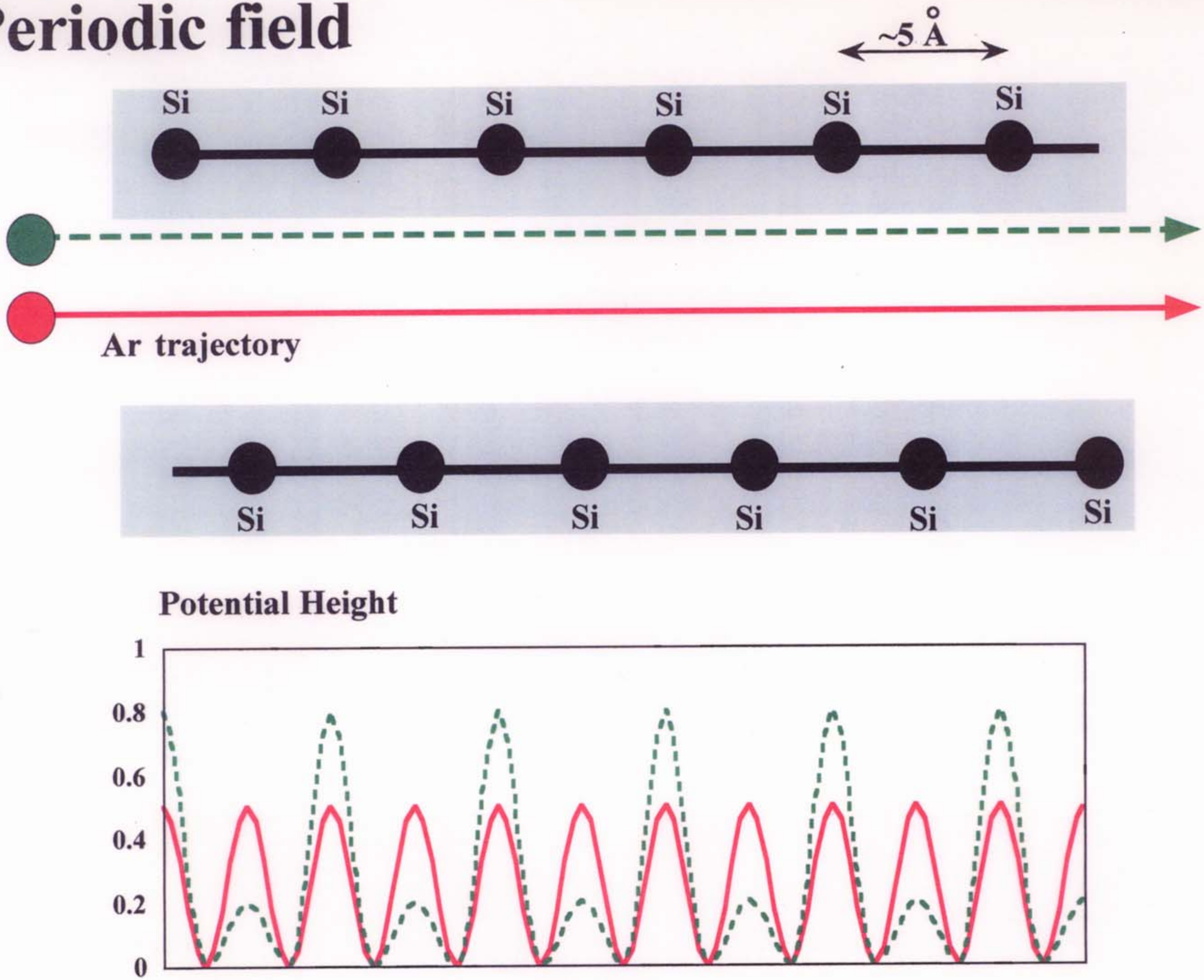


Characteristics of Heavy Ion Channeling

- Soft collision mainly with valence electrons and …
- Reduced charge exchange & energy loss
- Large stationary & oscillating electric crystal fields
  (~GV/cm) ⟶ RCE(Okorokov-effect)



Periodic field



What is RCE ?

- time-dependent perturbative potential

[frequency] = [velocity] / [length]

$$\nu = (\beta c) / (d/\gamma)$$

d: the lattice spacing

- energy of the perturbation: $h\nu$

difference of an internal energy level of the ion: E_{trans}

Resonant Coherent Excitation (RCE) condition

$$E_{trans} = k\,h\nu$$

k=1,2,3 ....

Proposed by Okorokov (1966)

Aimed Nuclear Excitation from the beginning

SOVIET JOURNAL OF NUCLEAR PHYSICS VOLUME 2, NUMBER 6 JUNE 1966

The Coherent Excitation of Nuclei Moving Through a Crystal

V. V. Okorokov

Institute of Theoretical and Experimental Physics, State Committee on Use of Atomic Energy

Submitted to JNP editor May 7, 1965

J. Nucl. Phys. (U.S.S.R.) **2**, 1009–1014 (December, 1965)

Some qualitative considerations are presented which lead us to expect the existence of coherent Coulomb excitation of nuclei passing through a crystal.

Title of our present research project (P32) at HIMAC

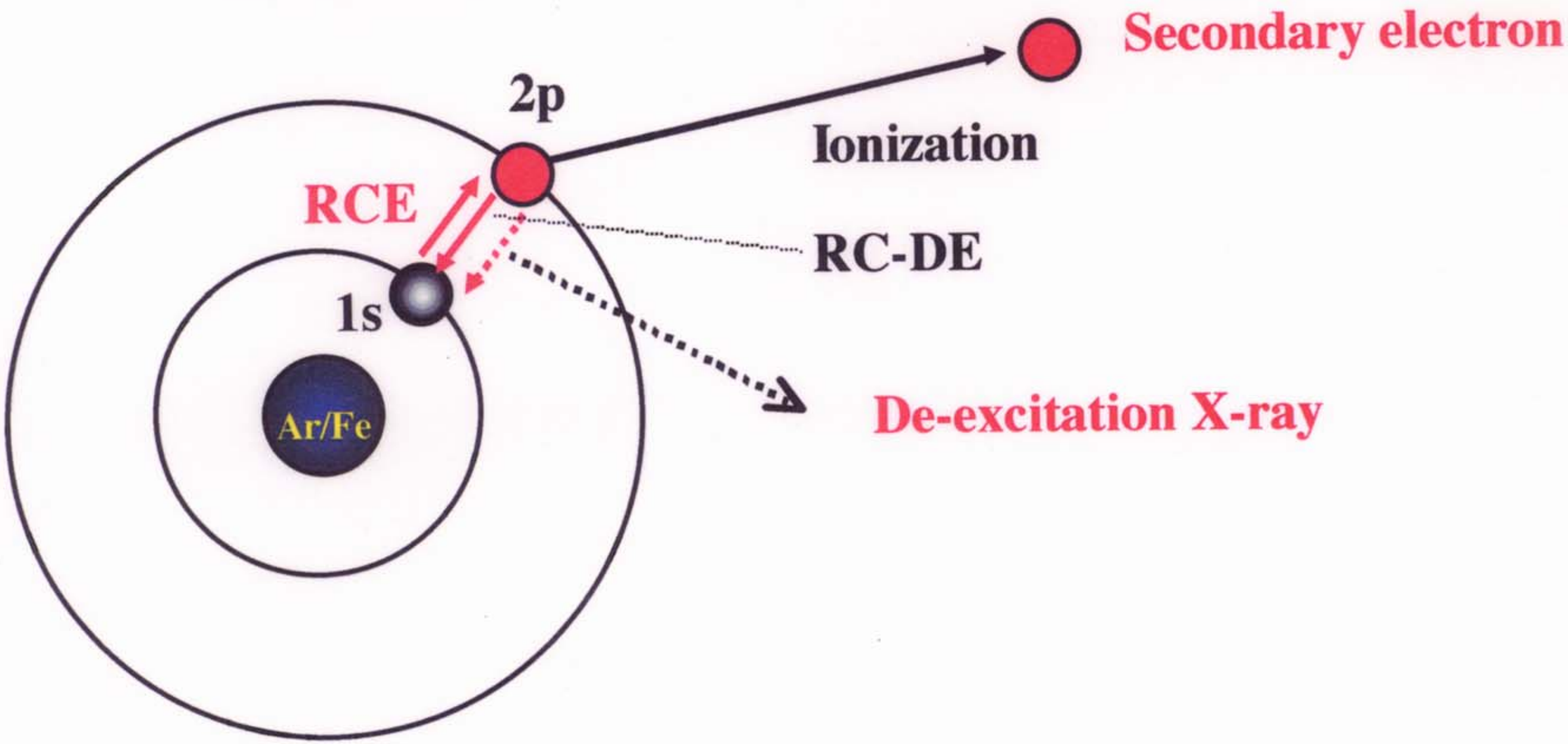
" 相対論的イオンビームによる核オコロコフ効果"

How to Observe RCE ?

1) Charge State of Projectile

2) De-excitation X-ray of Projectile

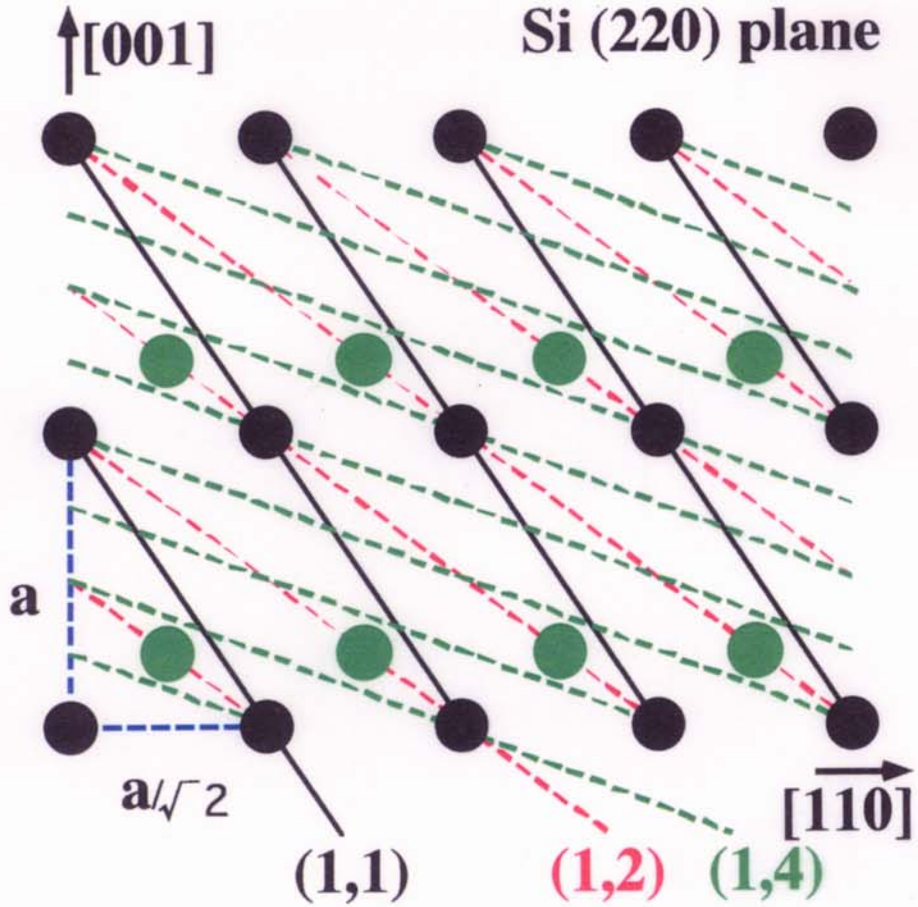
3) Convoy Electron



Planar Channeling

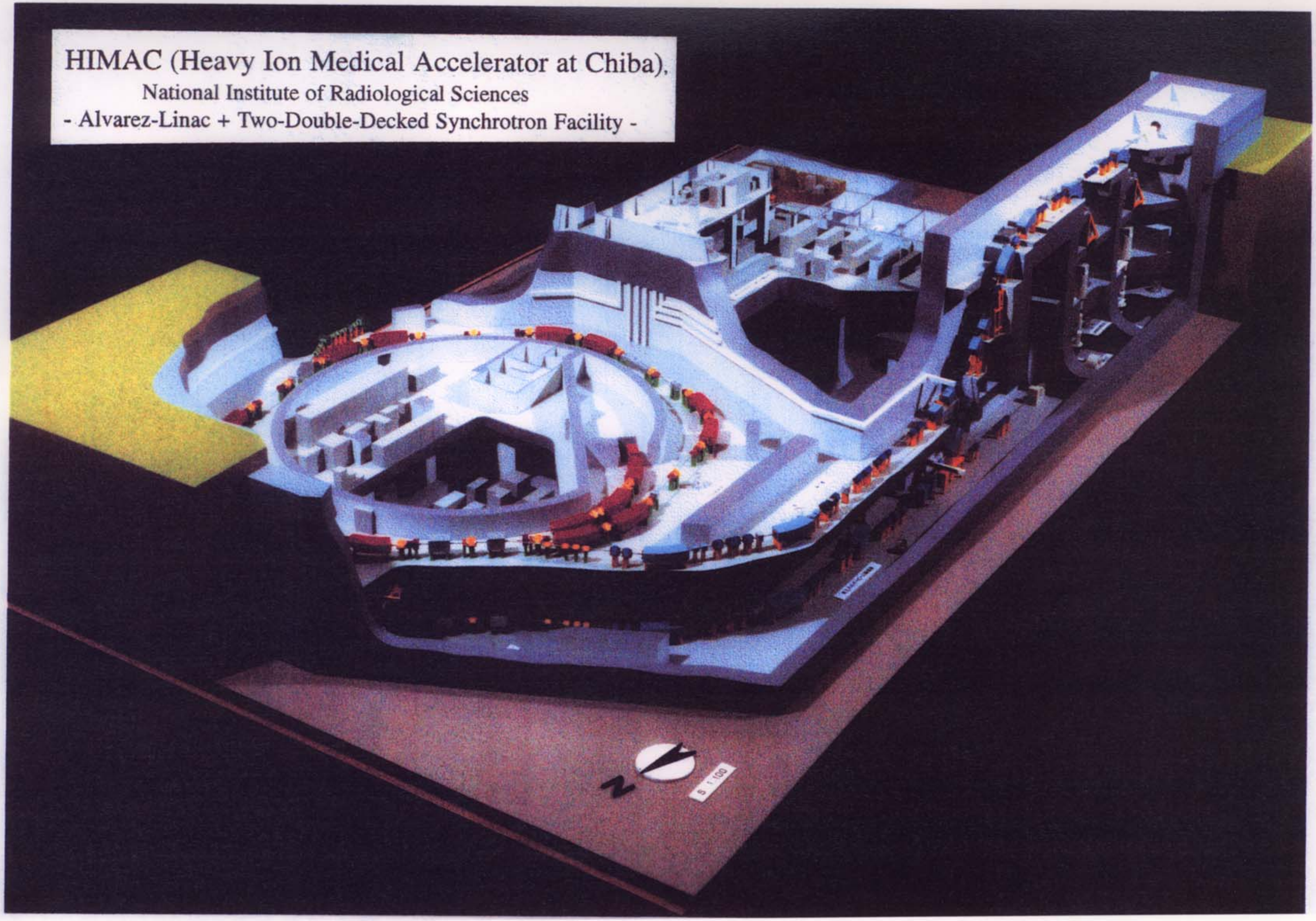
- RCE under the planar channeling by tilting the angle from the direction of the <110> axis in the (220) plane. The resonance condition is

$$k\cos(\theta)/(a/\sqrt{2}) + l\sin(\theta)/a = E_{trans}/\gamma\beta hc$$



k and l : integers
θ: a tilt angle from the <110> axis in the plane.

a : a lattice constant



HIMAC (Heavy Ion Medical Accelerator at Chiba),
National Institute of Radiological Sciences
- Alvarez-Linac + Two-Double-Decked Synchrotron Facility -

Advantage of Higher Ion Energy ~400MeV/u

- The lower order (1st) Fourier components of the crystal potential → large resonance

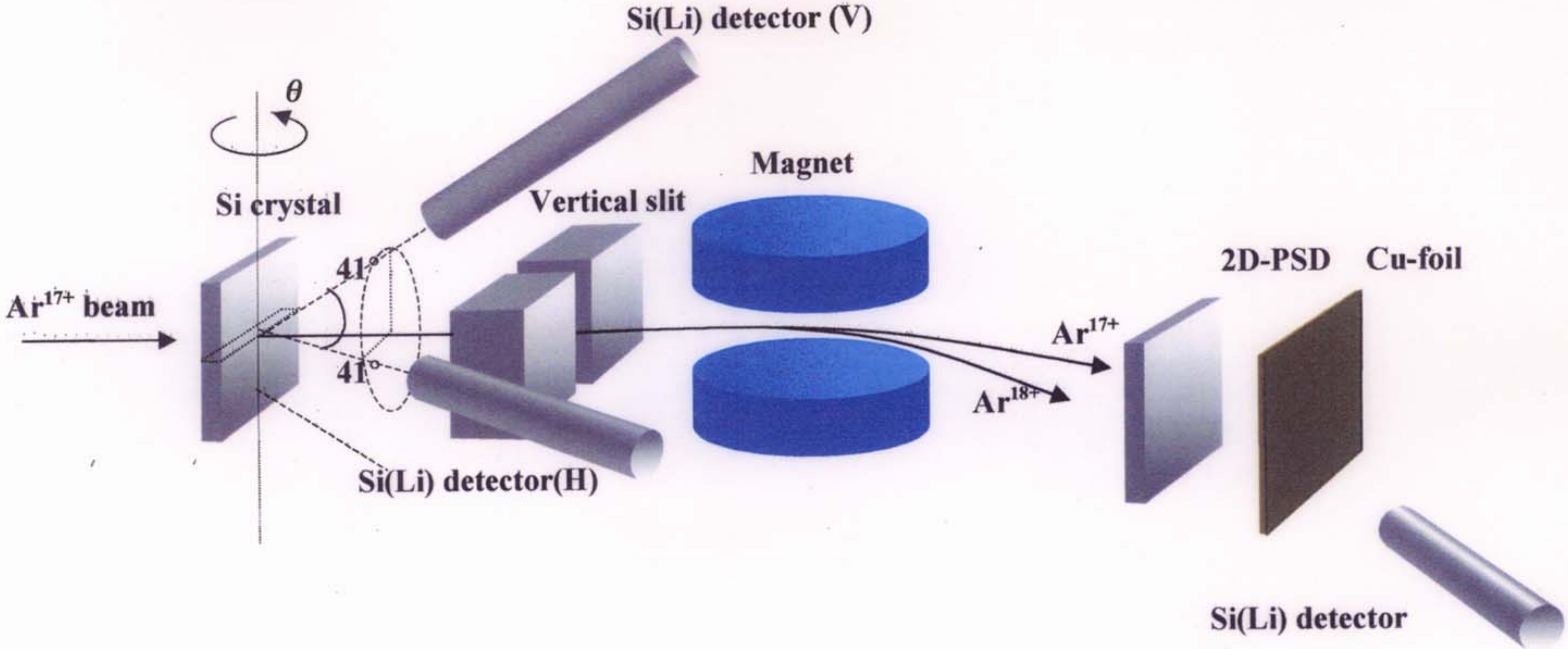
- Reduced charge exchange →

1. We can extract the resonance phenomena without being obscured by the charge exchange.

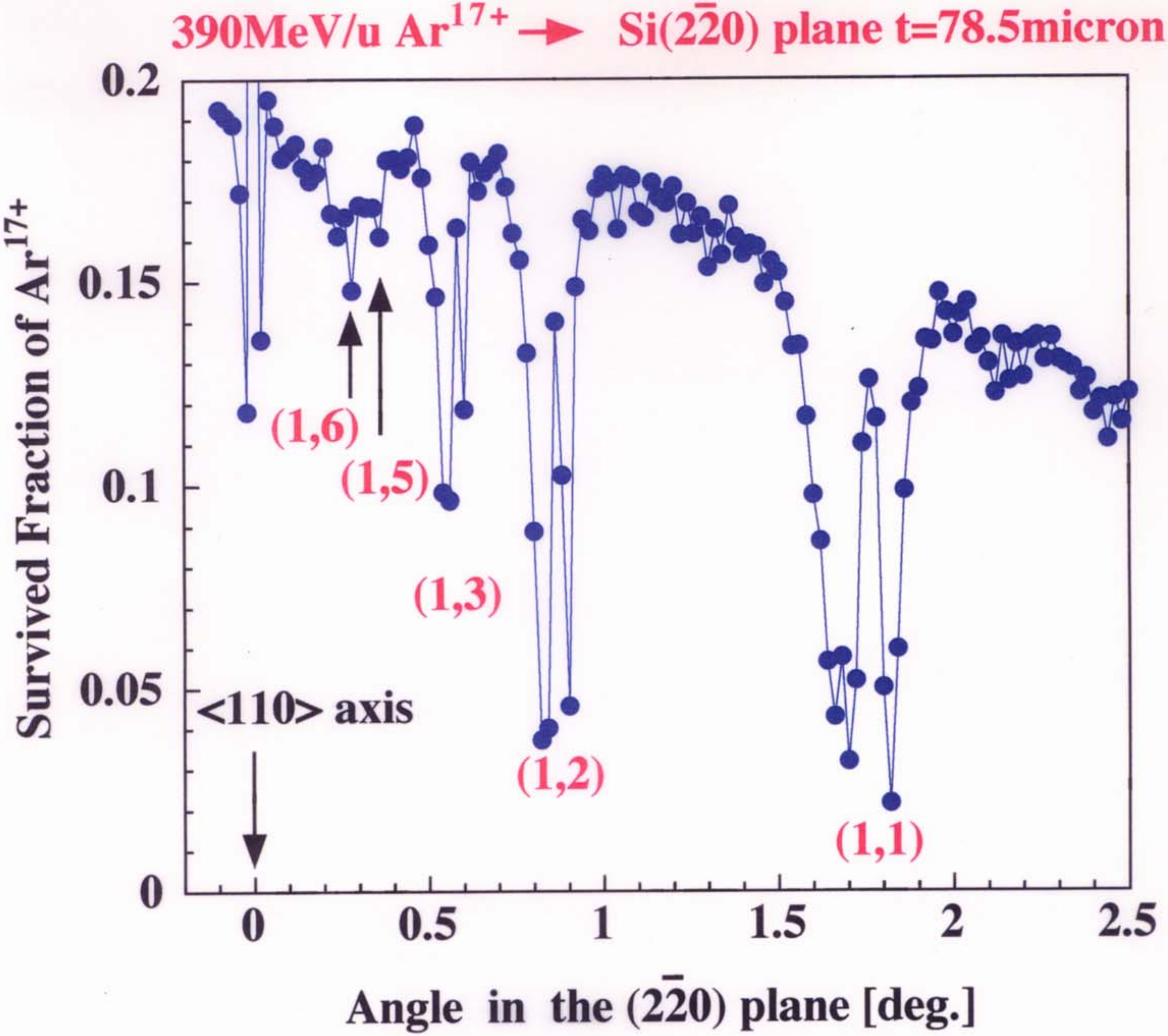
2. Large coherence → Sharp resonance

3. Thick crystals with good quality.

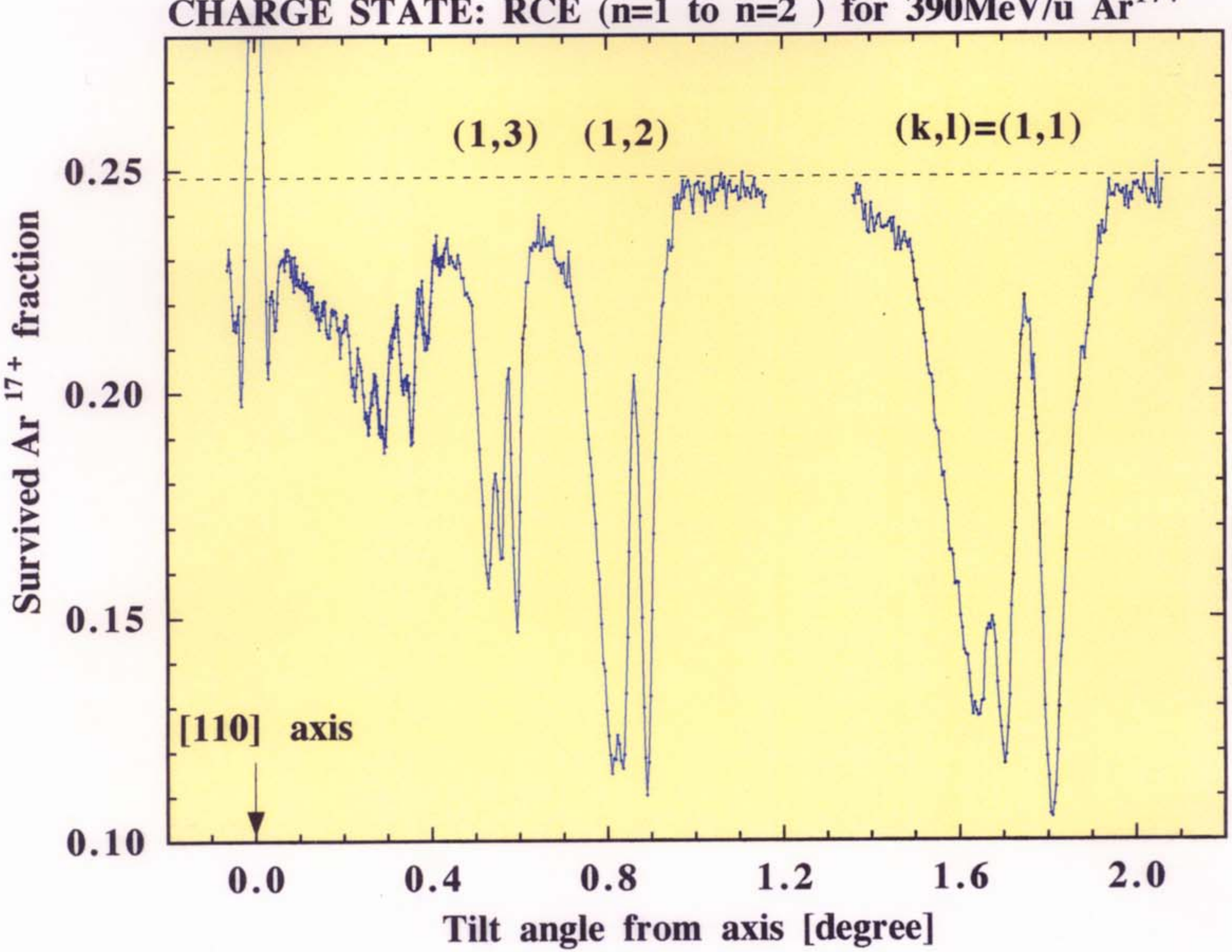
measurement of energy loss in crystal with a Si detector
→ probing trajectory



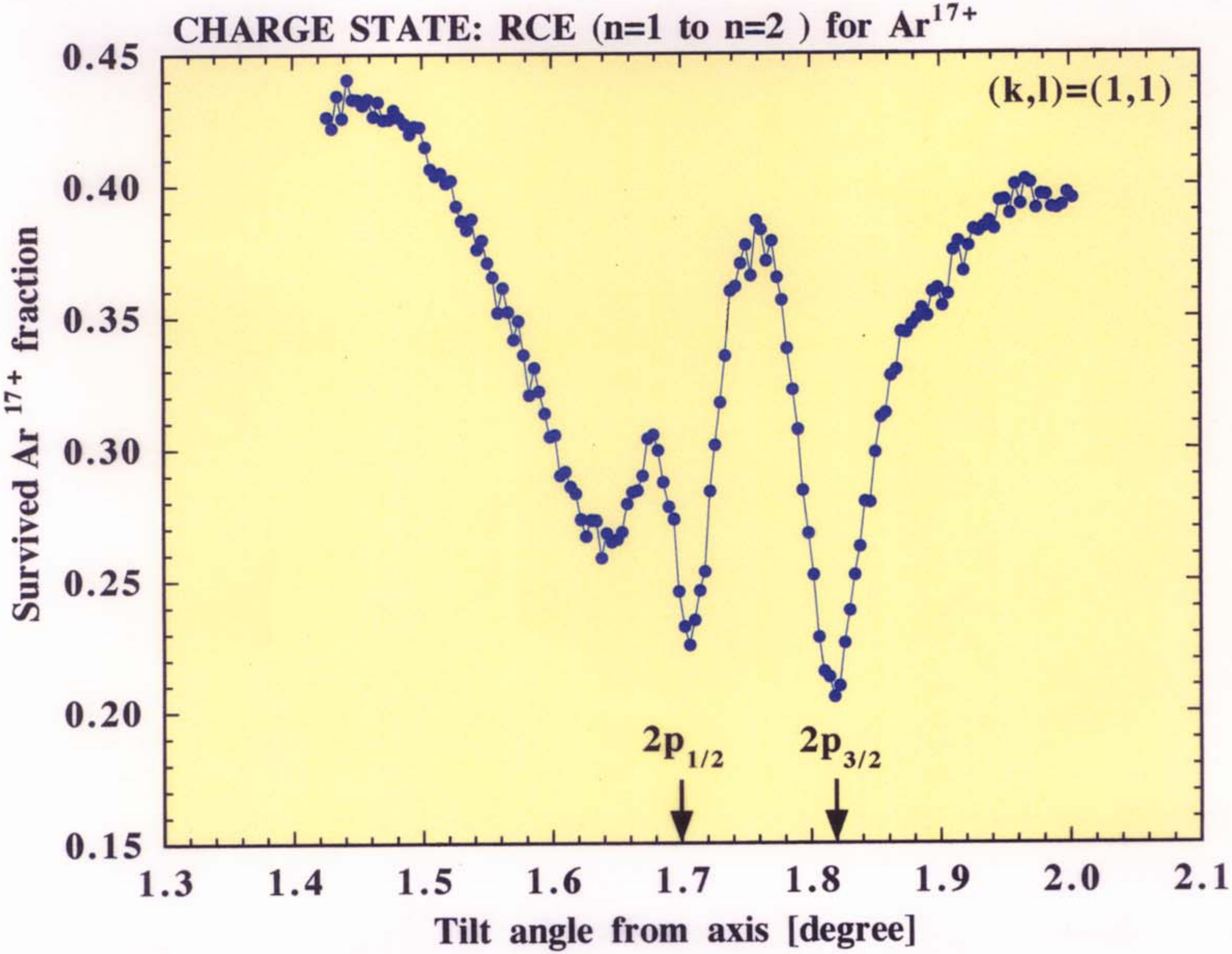
Schematic drawing of experimental setup for measuring the de-excitation X-rays



390MeV/u Ar17+ → Si(2$\bar{2}$0) plane t=78.5micron
Survived Fraction of Ar17+
0.2
0.15
0.1
0.05
0
(1,6)
(1,5)
(1,3)
(1,2)
(1,1)
<110> axis
0
0.5
1
1.5
2
2.5
Angle in the (2$\bar{2}$0) plane [deg.]



CHARGE STATE: RCE (n=1 to n=2) for 390MeV/u Ar17+
(1,3)
(1,2)
(k,l)=(1,1)
[110] axis
Survived Ar 17+ fraction
0.25
0.20
0.15
0.10
0.0
0.4
0.8
1.2
1.6
2.0
Tilt angle from axis [degree]



CHARGE STATE: RCE (n=1 to n=2) for Ar17+
(k,l)=(1,1)
Survived Ar 17+ fraction
0.45
0.40
0.35
0.30
0.25
0.20
0.15
2p1/2
2p3/2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
Tilt angle from axis [degree]

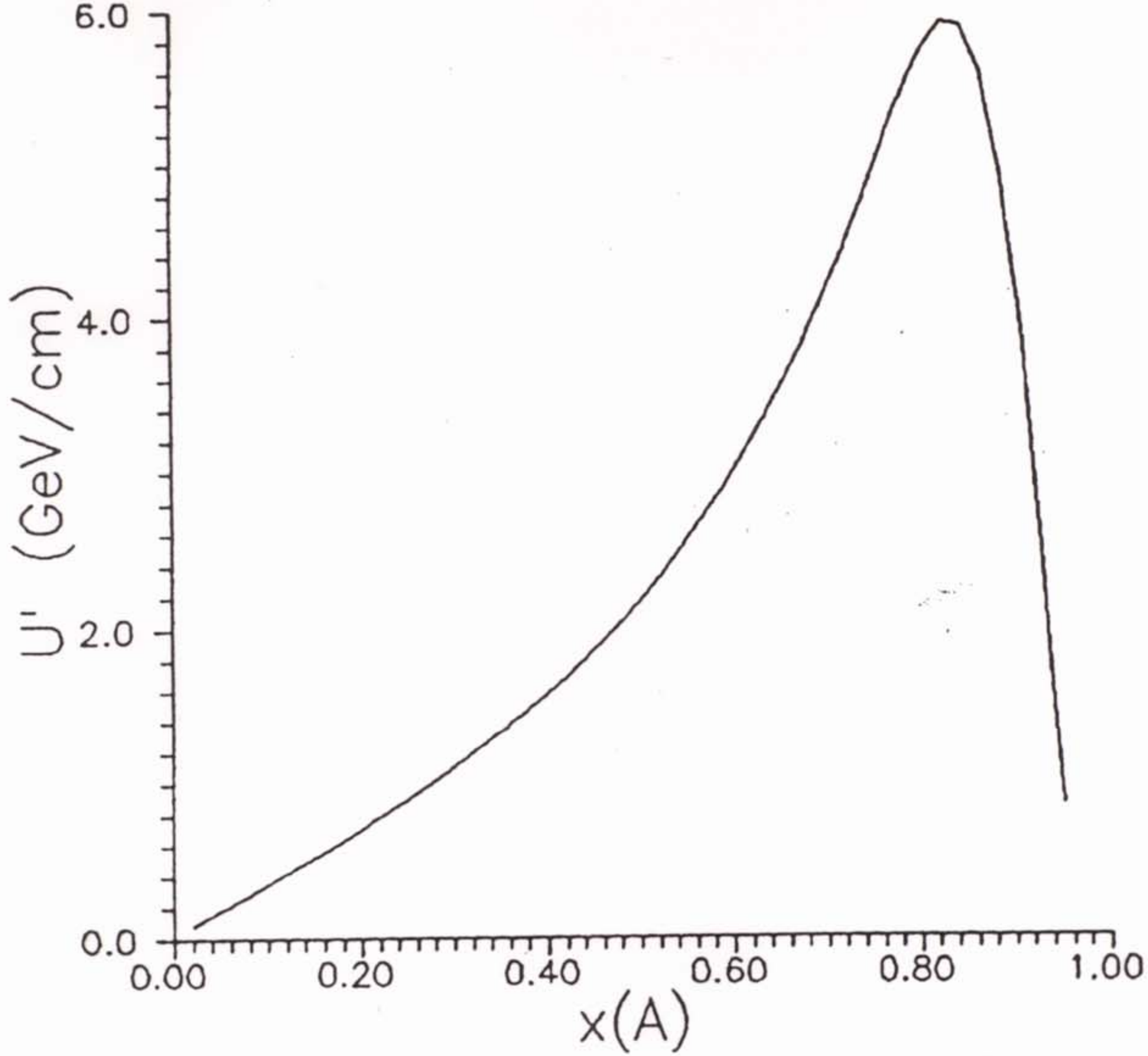
l-s interaction and Stark effect

Removal of the degeneracy of n=2 states due to

1. ***l-s* interaction originating in High-Z**
2. **Stark effect originating mainly in the static crystal field.**

- **a single peak at the higher energy side & a doublet peak at the lower energy side.**
- **a skewed single peak with a tail to the higher energy side, and a doublet also has a tail into the lower energy side.**

Static Electric Field in a Crystal

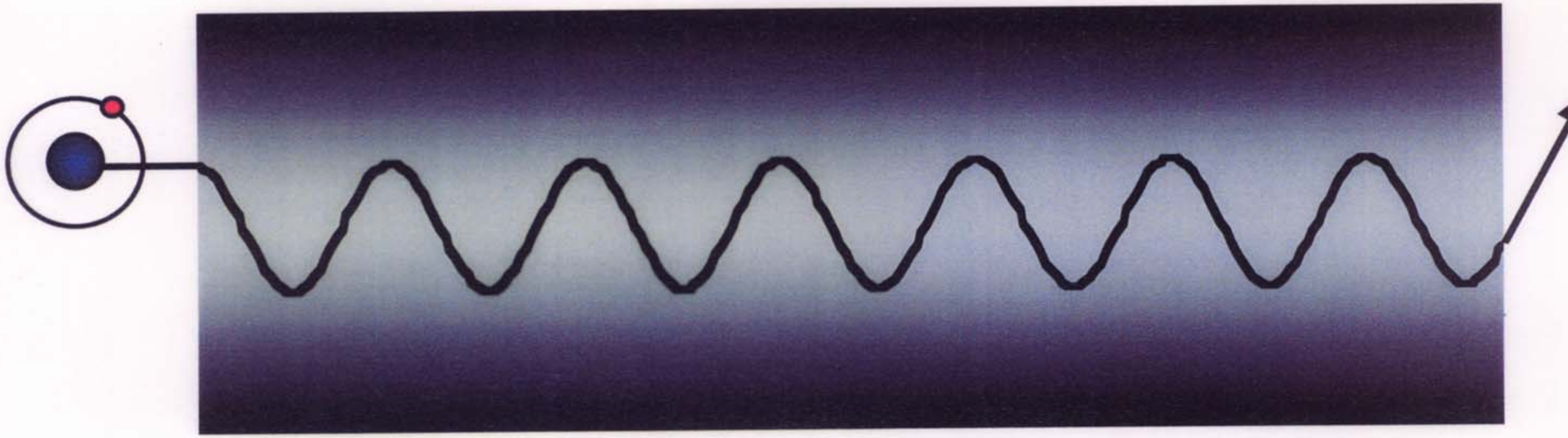


The interplanar electric field (Moliere) for the Si (110) channel

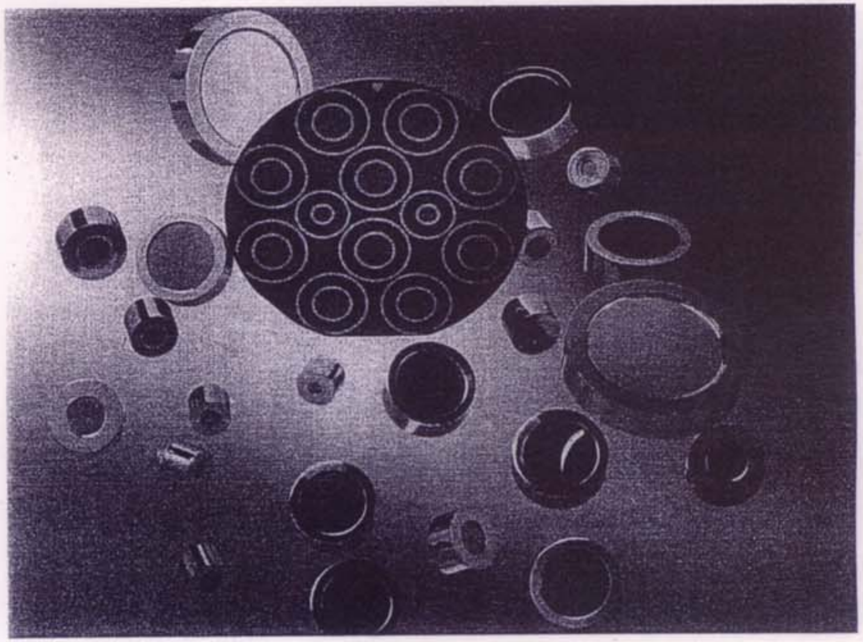
Energy loss vs trajectory (Planar Channeling)

Energy loss and an amplitude of the ion trajectory are related uniquely in the planar channeling

cf. axial channeling : statistical equilibrium



How to observe energy loss: SSD



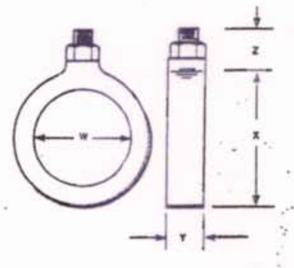
Usually
energy analyzer with
a combination of BIG magnets

↕

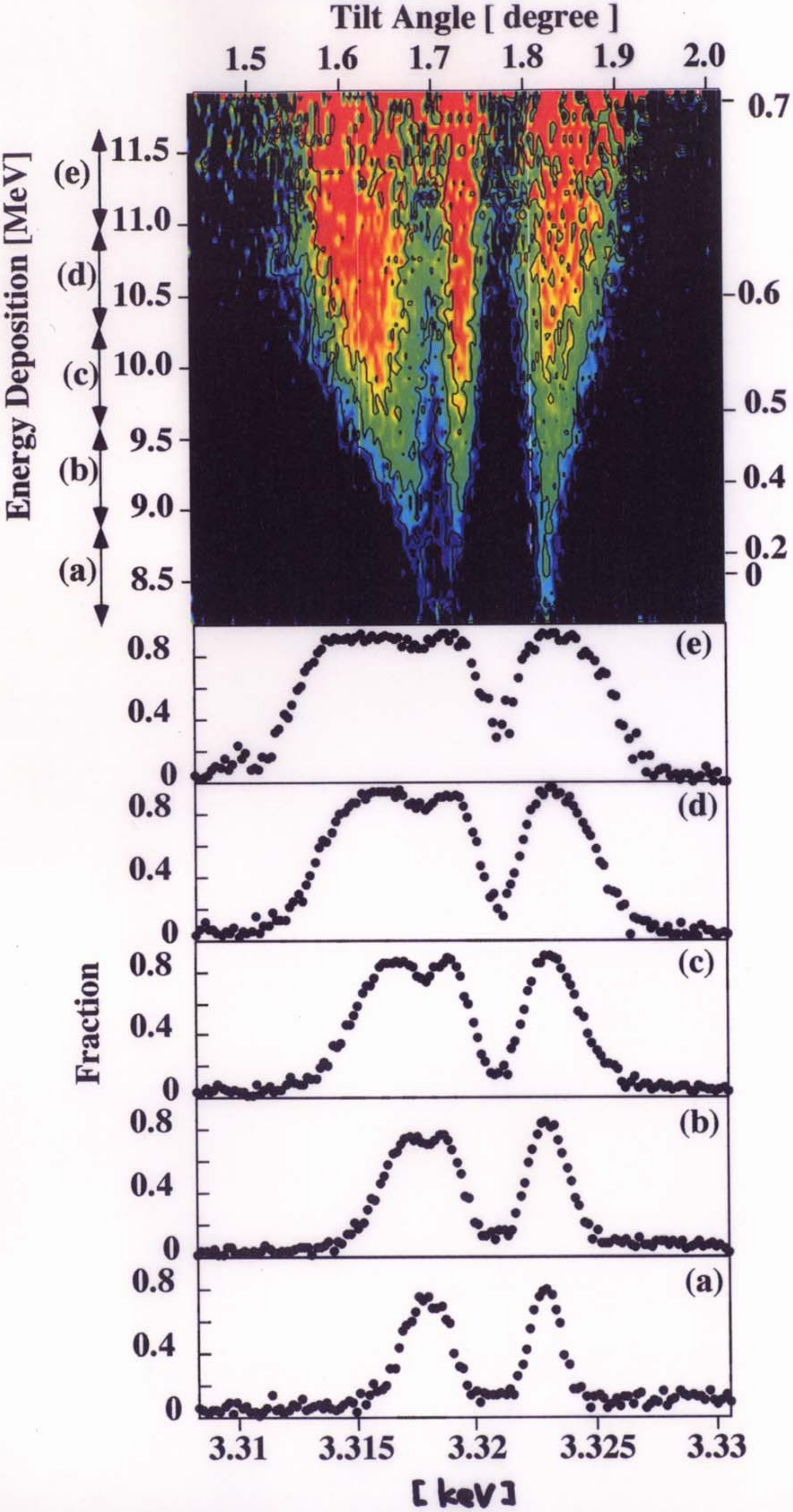
Silicon Surface barrier Detector
(SSD) for the ΔE measurement
in the transmission type experiment
(specially cut)

↓

measurement of energy deposition
in crystal probing trajectory

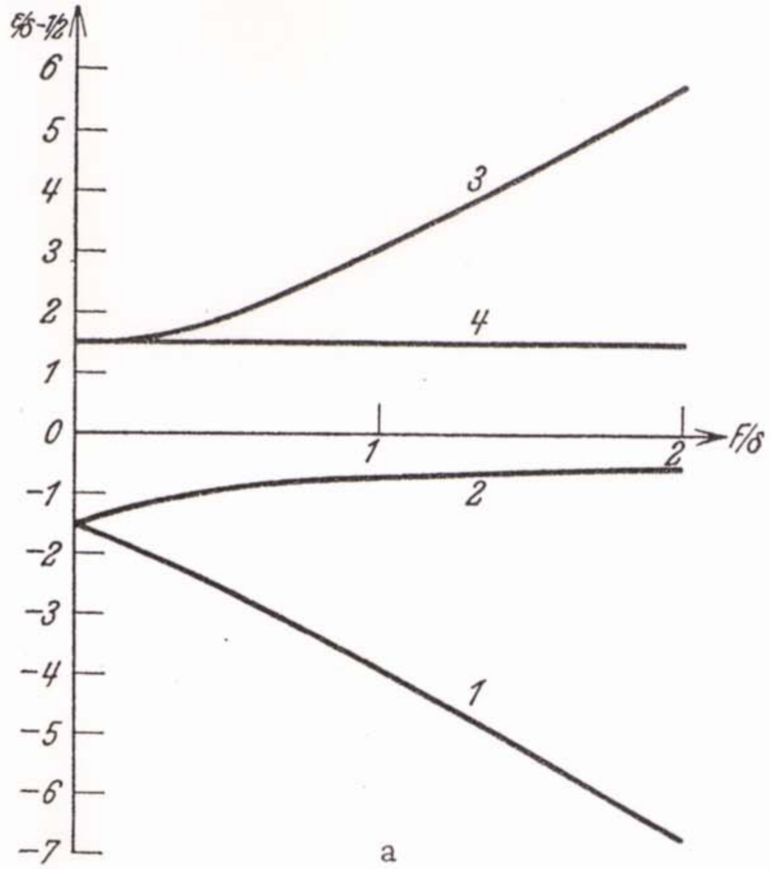


resolution ~20keV
(20keV/15.6GeV = ~ppm)



Tilt Angle [degree]
1.5
1.6
1.7
1.8
1.9
2.0
Energy Deposition [MeV]
(a)
(b)
(c)
(d)
(e)
8.5
9.0
9.5
10.0
10.5
11.0
11.5
Amplitude [Å]
0
0.2
0.4
0.5
0.6
0.7
Fraction
0
0.4
0.8
[keV]
3.31
3.315
3.32
3.325
3.33

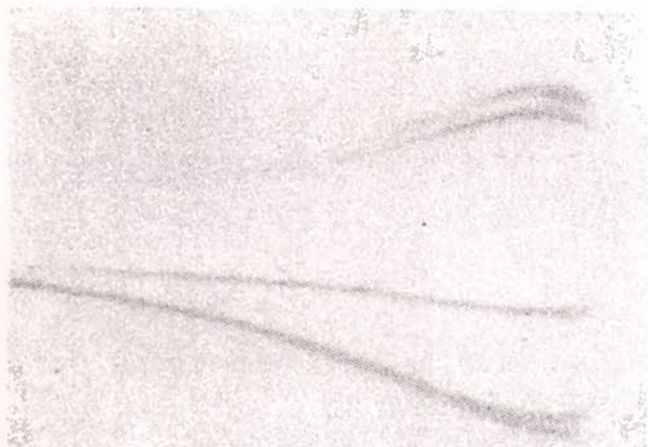
H. A. Bethe
(Handbuch der Physik 1933)

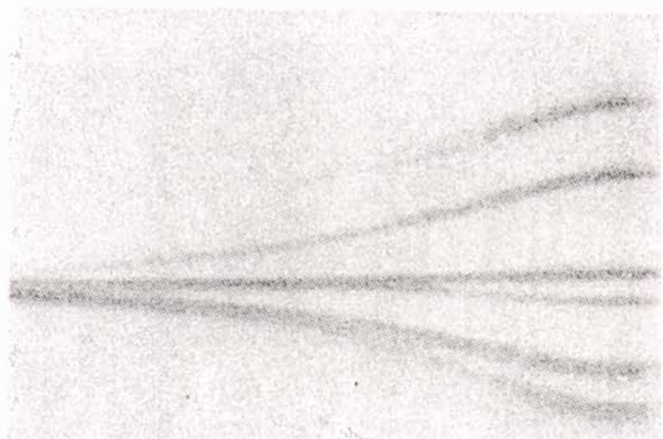


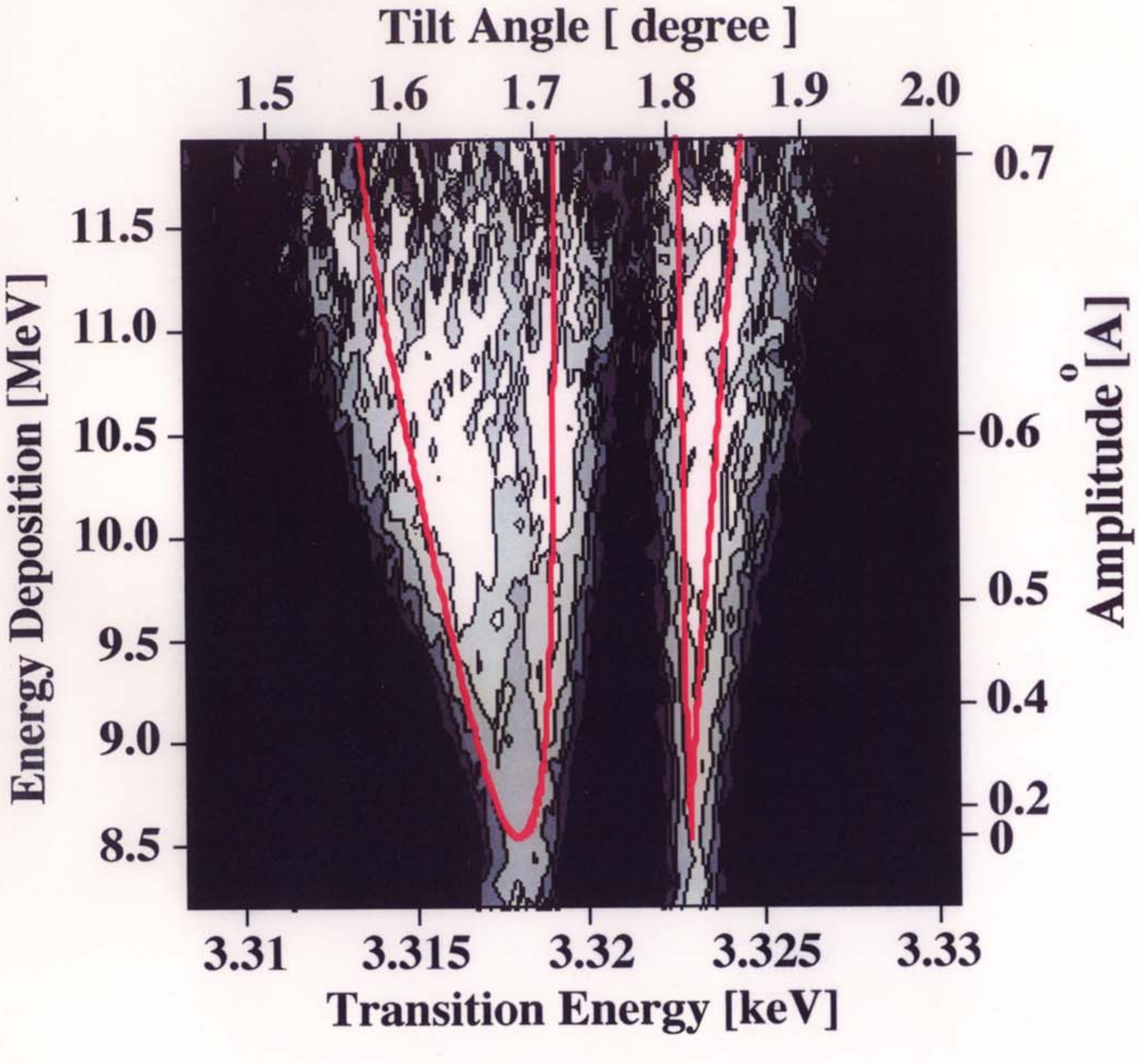
a

J. S. Foster
(Proc. Roy. Soc. Lon. 1928)

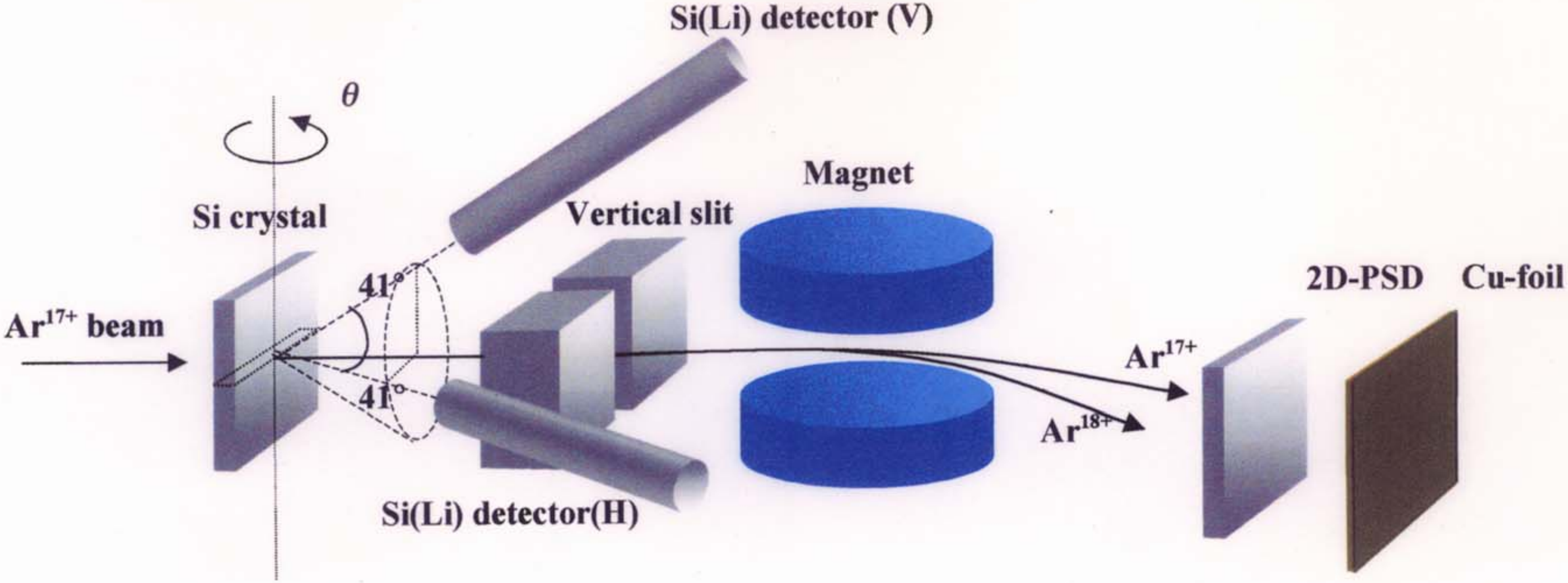
He λ=4388nm







Tilt Angle [degree]
1.5
1.6
1.7
1.8
1.9
2.0
Energy Deposition [MeV]
11.5
11.0
10.5
10.0
9.5
9.0
8.5
Amplitude [Å]
0.7
0.6
0.5
0.4
0.2
0
3.31
3.315
3.32
3.325
3.33
Transition Energy [keV]



Schematic drawing of experimental setup for measuring the de-excitation X-rays

Ar X-RAY: RCE (n=1 to n=2) for 390MeV/u Ar^{17+}

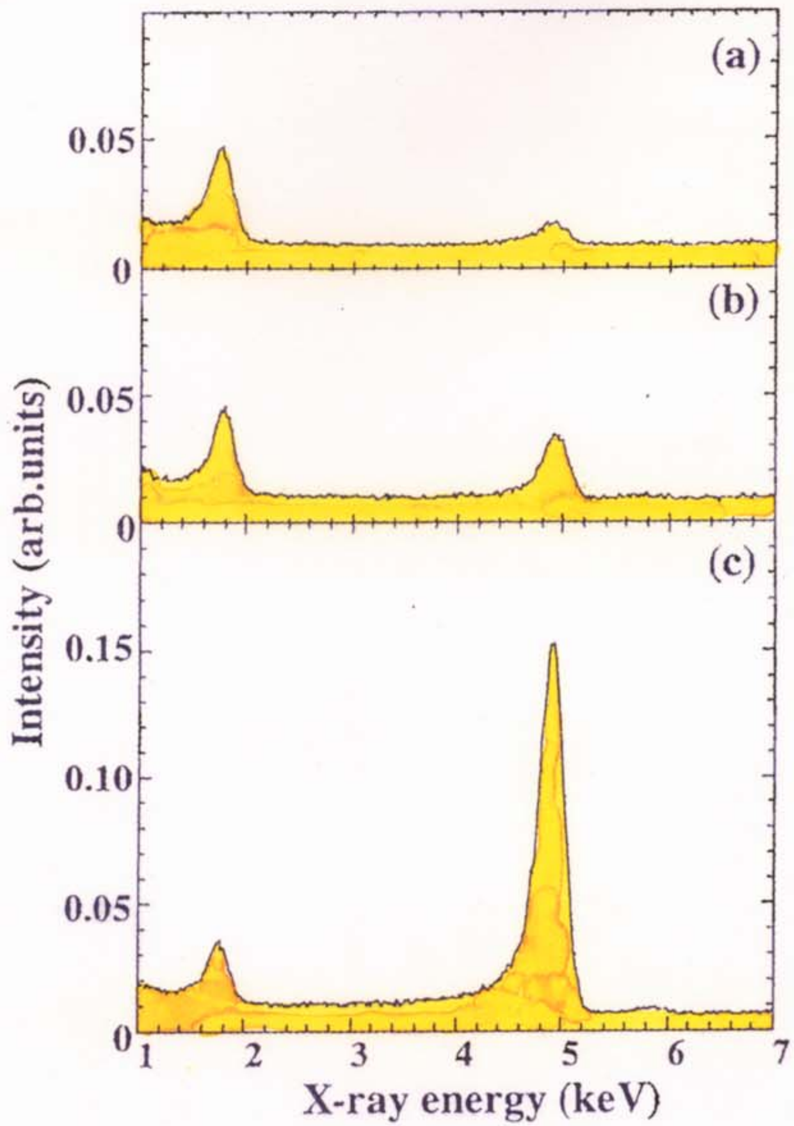
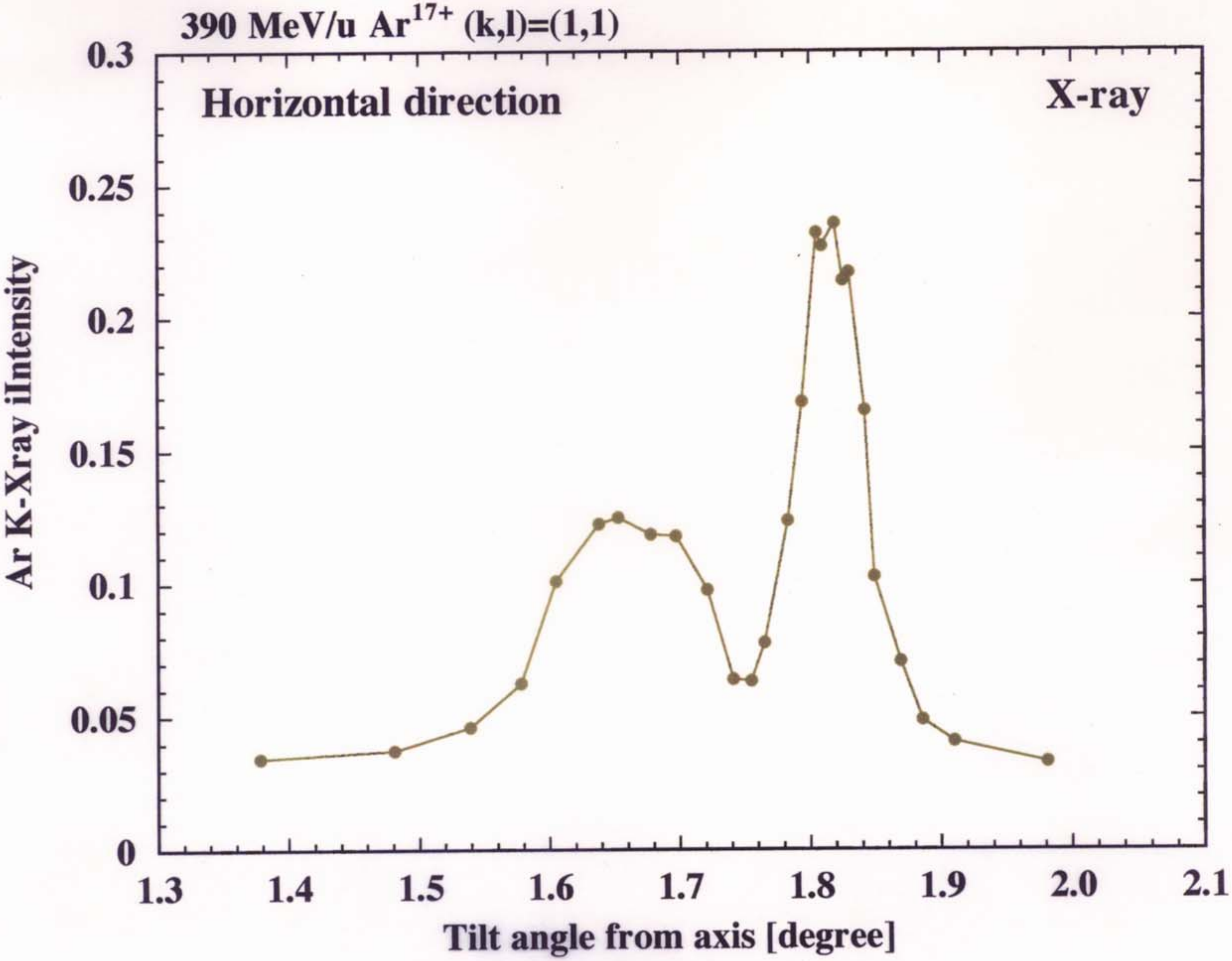


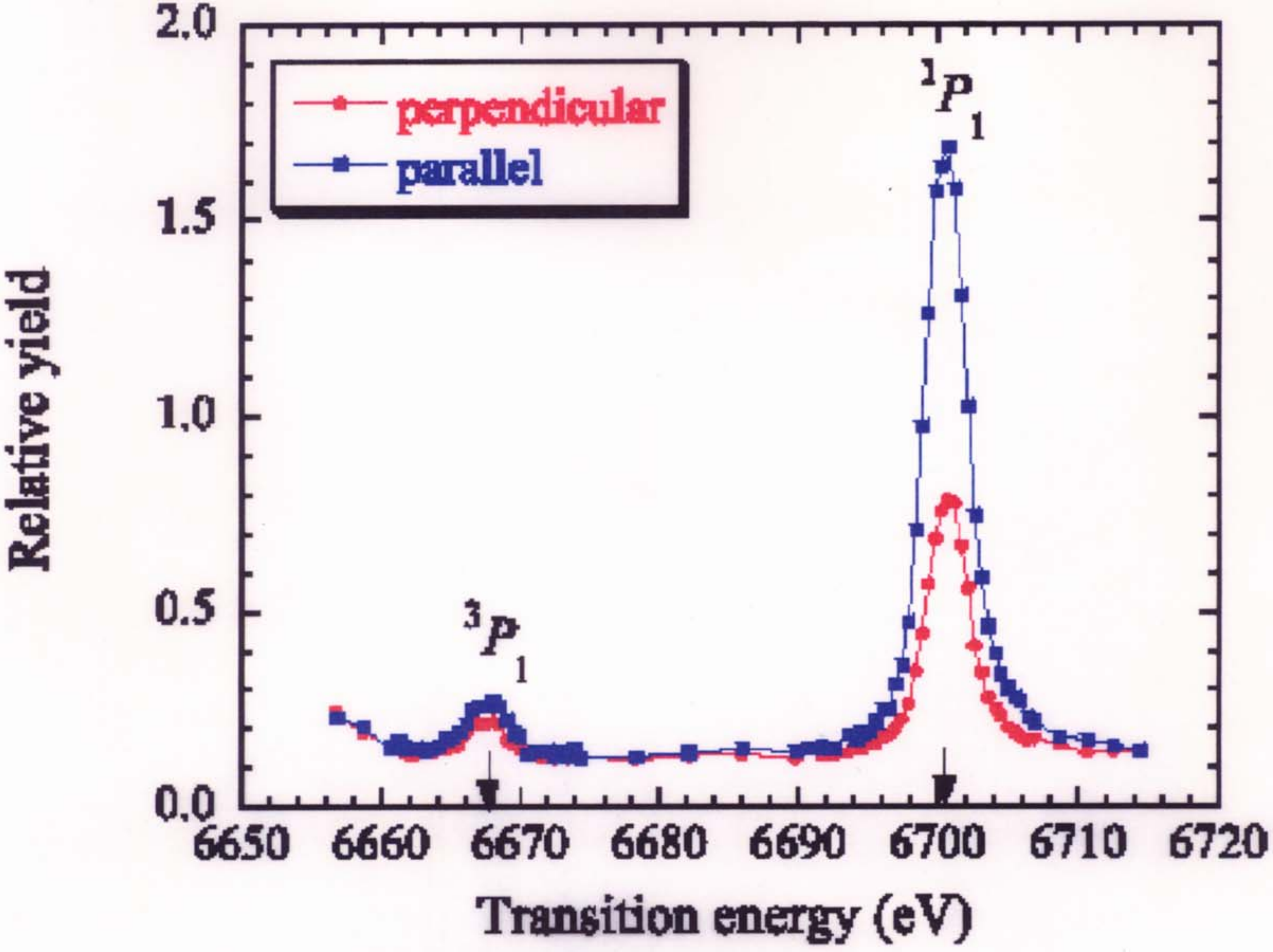
Fig. 2. X-ray spectra for (a) random incidence, (b) channeling (off-resonance) and (c) RCE condition.

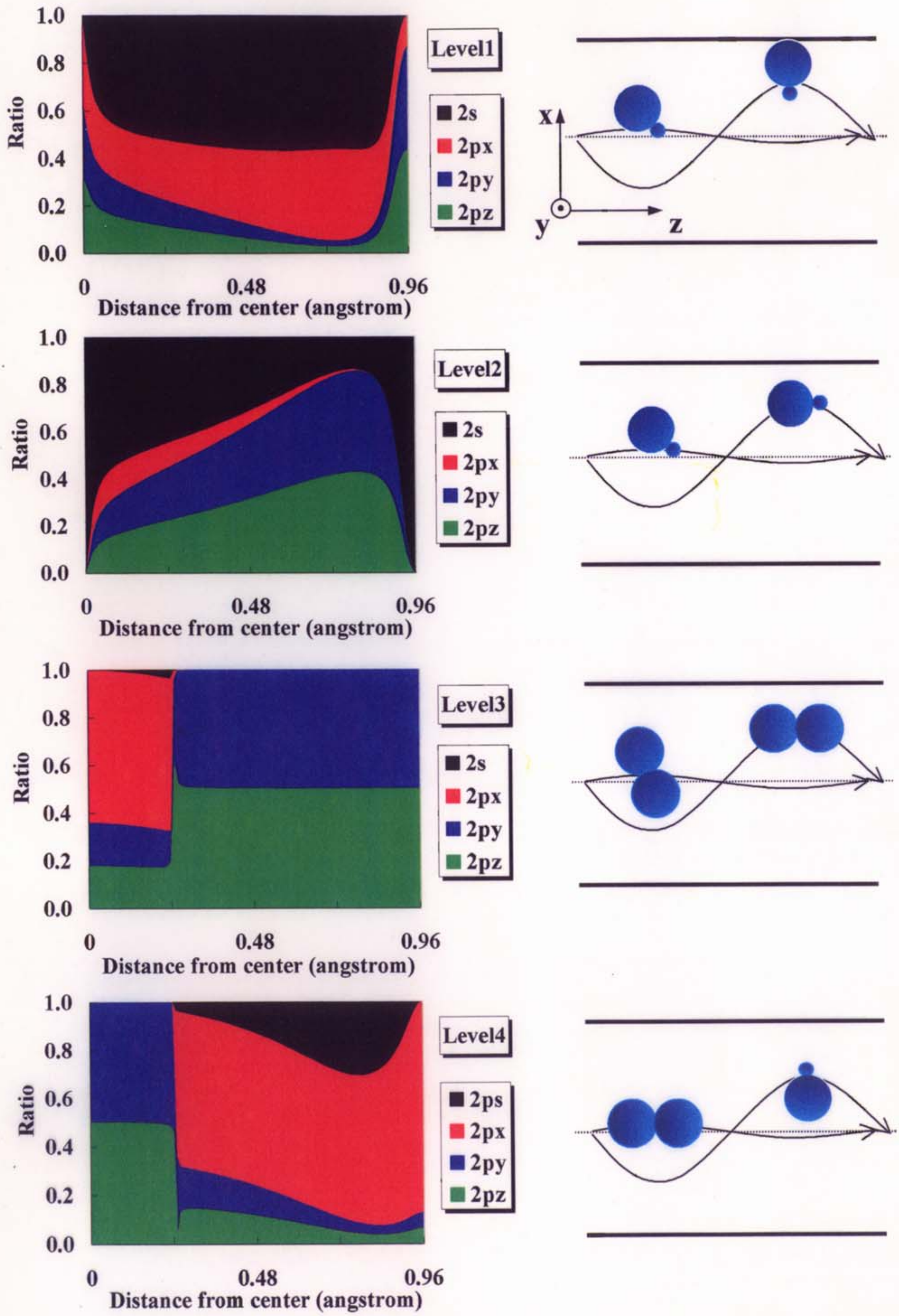
De-excitation X-ray of Projectile



De-excitation X-rays of Projectile

423 MeV/u Fe^{24+} (k,l)=(2,1)




Ratio
1.0
0.8
0.6
0.4
0.2
0.0
0
0.48
0.96
Distance from center (angstrom)
Level1
2s
2px
2py
2pz
x
y
z
Level2
2s
2px
2py
2pz
Level3
2s
2px
2py
2pz
Level4
2ps
2px
2py
2pz

High precision spectroscopy

- **Width of the j=3/2 peak for the best channeled ion:**

  0.64eV: $\delta E/E = 2\times10^{-4}$

  Observed : 1.1eV
  Beam angular divergence: $\delta\theta$=~0.1mrad -> 0.22eV
  Energy width of the projectile: $\delta E_0/E_0$=~2x10^-4 ->0.78eV

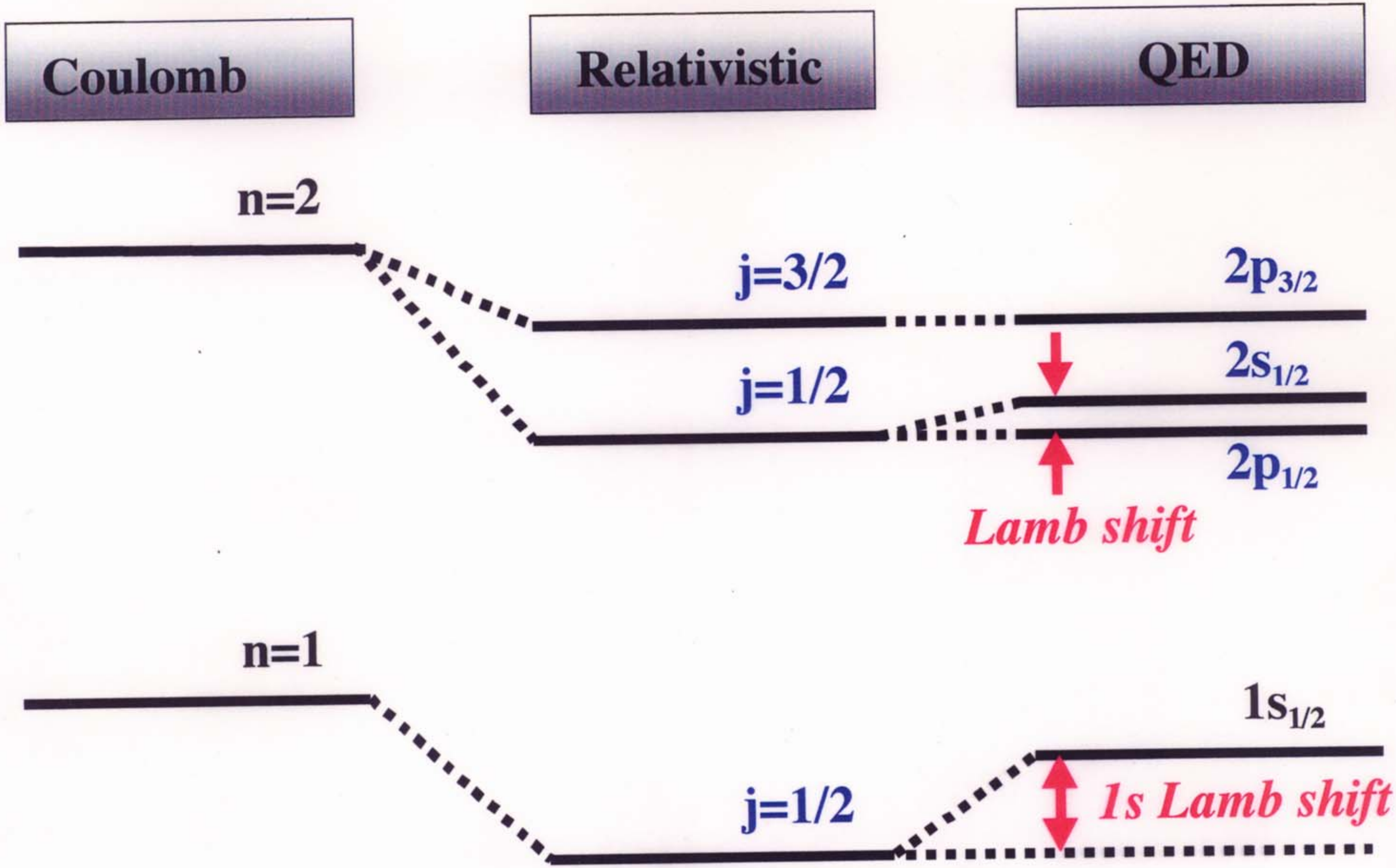
  the number of atomic strings N:
  $\delta E/E$= ~1/N then N= ~5×10^3 = ~μm

  High coherence achieved by the large ion velocity !

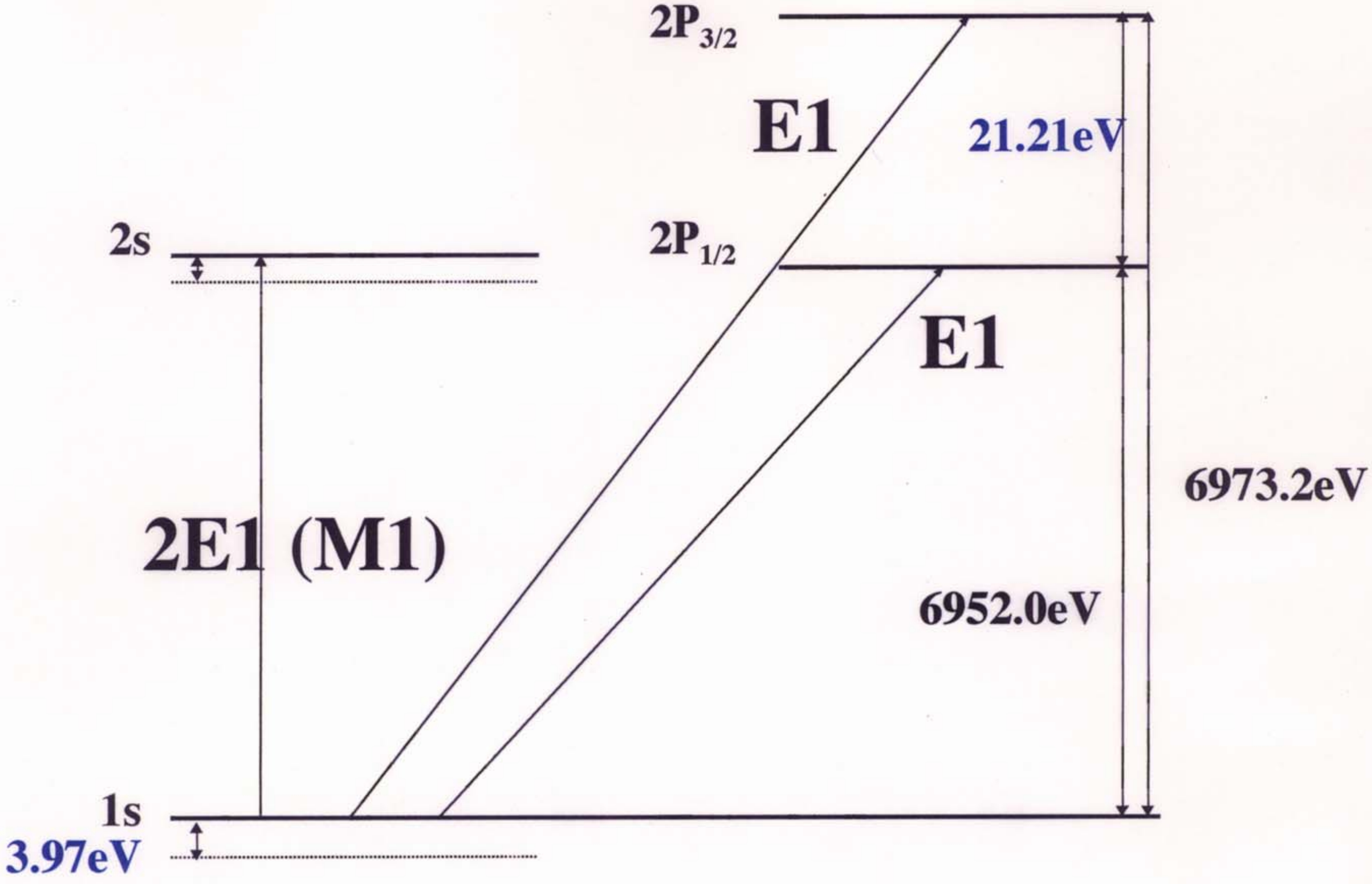
- **Peak position of j=3/2:**

  ~0.05eV i.e. 10 ppm

Enegy levels of hydrogen-like system



Hydrogen-like Fe



1s Lamb shift

Th. Stöhlker (HCI-conf. '97)

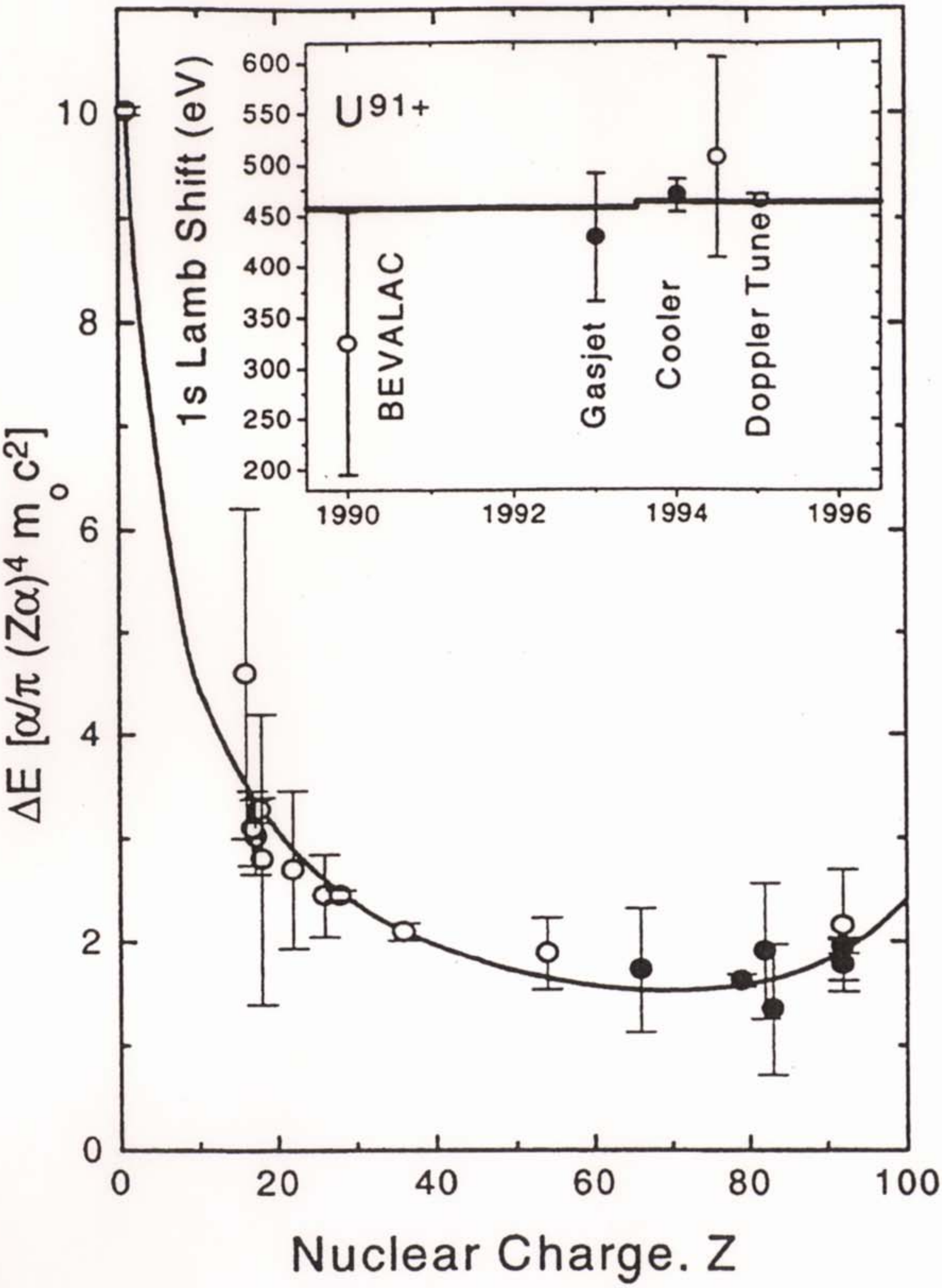


Fig. 11. All available experimental results for the 1s Lamb shift in high-*Z* ions in comparison with theoretical predictions [3]. In the inset the available data for U^{91+} are depicted, where the solid points refer to the experiments performed at the ESR. The solid line shows the theoretical predictions of Ref. [3] and Ref. [6], respectively.

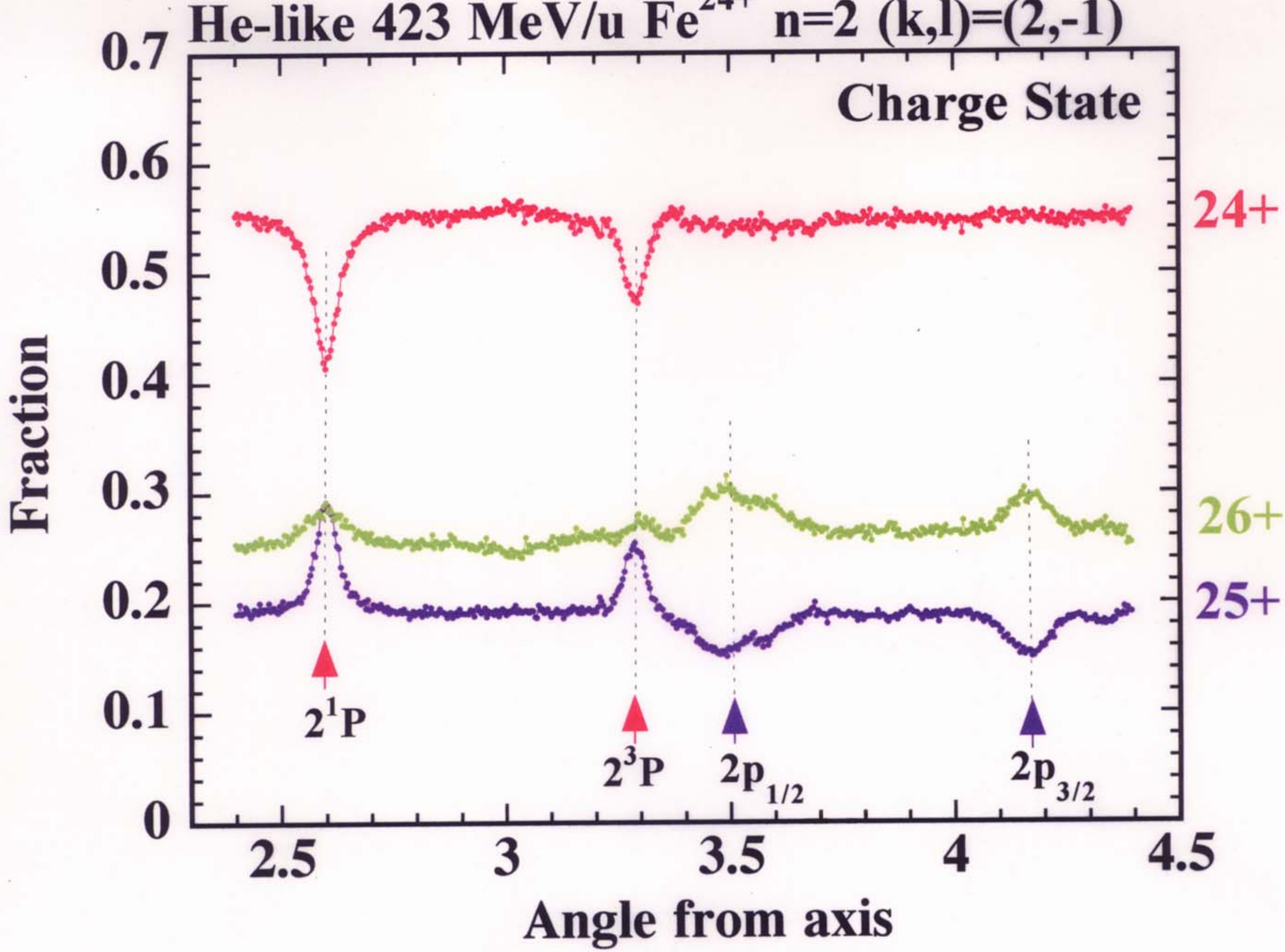
High Precision Spectroscopy of He-like system

1) First:

Measurement of the projectile energy by $2p_{3/2}$ of H-like system

2) Second:

Determination of 2^1P and 2^3P of He-like system by using the above projectile energy



He-like 423 MeV/u Fe^{24+} n=2 (k,l)=(2,-1)
Charge State
Fraction
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
24+
26+
25+
2^1P
2^3P
$2p_{1/2}$
$2p_{3/2}$
2.5
3
3.5
4
4.5
Angle from axis

Summary

Atomic RCE --- Highly Charged Heavy Ions

Strong field & Good coherence in ~400 MeV/u energy

- ***l-s* interaction originating in High-Z**
- **Stark effect originating in the static crystal field**
- **Excitation to higher level: n=2, 3, 4, 5…**
- **Multi electron system: H-like, He-like, Li-like …**
- **Higher Z-ion: Ar, Fe …**

High Precision Spectroscopy: Lamb shift